national accelerator laboratory

EXP-59
March 8, 1974

ACCELERATOR EXPERIMENT: Beam Instability Enhanced by a Pocket of High Pressure in the Main Ring

Experimentalists: Main-Ring Group

Date Performed: March 5, 1974

Measurement

The average vacuum pressure was $\sim 10^{-7}$ mmHg. A local high-pressure bump was created from pump station E23 to E27 (see Fig. 1). The bump is between 10^{-5} and 10^{-4} mmHg over a range of ~20 m. Because of this, an increase of, at most, a factor 2 is expected in the average pressure. We believe this increase is not enough to cause any catastrophic effect from ordinary gas scattering. The bump was applied for long periods of time, over several main-ring cycles.

The beam was injected in 12 booster batches for a total intensity of 6.5×10^{12} ppp, and then accelerated to 300 GeV.

Both radial and vertical dampers were on.

An instability occurred suddenly in correspondance of ~50 GeV No coherent bunch-to-bunch oscillations were noticed. Several bunches, in a random pattern, had their intensity reduced, and some of them also disappeared. The loss was caused by a horizontal blow-up, which took place in about 40 msec and suddenly stopped at the intensity of $\sim 5 \times 10^{12}$ ppp. A typical oscillogram is shown in Fig. 2.

In another run, the intensity has about 2×10^{12} ppp, again with 12 booster batches. The beam was stable all the way up.

Lowering the number of booster batches with the largest number of protons per bunch, has the effect to make the beam stable up to a total intensity of $\sim 4 \times 10^{12}$ ppp.

Changing the tune in the range 19.25 - 19.28 ($\nu_x \sim \nu_y$) had no effect on the beam stability.

A Theory

Let μ be the number of pairs of ions produced per unit of time and per proton in the bump of high pressure. Also, let τ_e and τ_i be the lifetime, respectively, of the electrons and the ions. Because the proton beam is bunched, the electrons, once produced by the passage of one bunch, easily escape between two bunches if their kinetic energy is at least of 1 or 2 eV. Thus τ_e is roughly half of the bunch length expressed in unit of time. Because their mass is larger and because their kinetic energy is lower, the ions take more time to escape. Roughly, τ_i is of the order of one or few revolution periods.

We shall calculate the effect of the proton beam on the ions and electrons, and the effect of these on the proton beam, but we shall disregard the interaction between ions and ions, electrons and electrons, ions and electrons and protons and protons.

From the point of view of the electrons and ions, the proton beam has a uniform density with radius a. Its barycentre is making small, either radial or vertical, oscillations described by

$$z_p = z_o \exp i(n\theta - \omega t) \ . \qquad (1)$$

The equation of motion is

$$\ddot{z} + \kappa^2 (z - z_p) = 0 \qquad (2)$$

where, for the electrons,

$$\kappa^2 = \frac{N_e^2}{\pi R\ a^2\ m_e} = \kappa_e^2$$

and, for the ions,

$$\kappa^2 = \frac{-N_e^2}{\pi R\ a^2\ m_i} = -\ \kappa_i^2\ .$$

N is the total number of protons, $2\pi R$ the accelerator circumference and m_e, m_i the mass, respectively, of an electron and of an ion.

Since (2) is linear, we can calculate the motion of the electron barycentre and of the ion barycentre by taking mean initial conditions. For a pair of ions born at time t_1 these are

$$z = z_0 \exp i(n\theta-\omega t_1)\ ,\ \dot{z} = 0\ . \tag{3}$$

The mean displacement of either species at θ, t is obtained by multiplying the solution of (2) with initial conditions (3) by $\frac{1}{\tau}\exp(t_1-t)/\tau$ and integrating dt_1 from $-\infty$ to t. This gives, provided $\mathrm{Im}\ \omega > -1/\tau$,

$$\langle z\rangle = z_p \frac{\kappa^2-i\omega/\tau+1/\tau^2}{\kappa^2-\omega^2-2i\omega/\tau+1/\tau^2} \tag{4}$$

where, for the electrons,

$$\langle z\rangle = \langle z_e\rangle\ ,\ \kappa^2 = \kappa_e^2\ ,\ \tau = \tau_e$$

and, for the ions,

$$\langle z\rangle = \langle z_i\rangle \quad , \quad \kappa^2 = -\kappa_i^2 \quad , \quad \tau = \tau_i \ .$$

Let us write now the equation of motion of the barycentre of the proton beam

$$\ddot{z}_p + \nu^2 \Omega^2 z_p = 2\nu\Omega^2 \mu\Delta\left[\tau_e(\langle z_e\rangle - z_p) - \tau_i(\langle z_i\rangle - z_p)\right] \tag{5}$$

where Ω is angular revolution frequency and ν is the number of betatron oscillations per turn. Eq. (5) applies at the location of the high-pressure bump, otherwise the r.h. side is identically zero.

The r.h. side of (5) is a periodic function of θ and can be replaced by the corresponding Fourier series expansion. Since we are looking for the effect on the collective mode (1), we shall keep only the corresponding driving term and ignore all the other "non-resonating" terms. Thus, we have to solve Eq. (5) with

$$\Delta = \frac{Ne^2}{2\pi R \ a^2 \ \gamma m_p \ \nu\Omega^2} \alpha \tag{6}$$

where m_p is the mass of a proton, γ the ratio of the total energy to the rest energy and α the fraction of the accelerator circumference occupied by the high-pressure bump.

The beam is locally, 100%, neutralized if $\mu\tau_e \sim 1$ and $\mu\tau_i \ll 1$. These conditions are not fulfilled for a bunched beam, because generally $\tau_i \gg \tau_e$ and an excess of ions is expected. Eq. (6) gives the ν-shift that would be caused by 100% neutralization.

Inserting (1) in (5) gives, for $\Delta \ll \nu$,

$$\omega = \Omega\left\{n\pm\left[\nu-\mu\tau_e\ \Delta\left(\frac{\langle z_e\rangle}{z_p}-1\right)+\mu\tau_i\ \Delta\left(\frac{\langle z_i\rangle}{z_p}-1\right)\right]\right\} \tag{7}$$

where $\langle z_e\rangle$ and $\langle z_i\rangle$ are given by (4). For small enough $\Delta\mu\tau$ one can usually approximate by putting $\omega = (n\pm\nu)\Omega$ at the r.h. side of (7).

The motion is <u>unstable</u> when $\mathrm{Im}(\omega)$ is positive. If $\mu\tau_e$ is not severely too small compared to $\mu\tau_i$, the mode with the largest growth rate occurs at the "electron resonance", which, according to (4), is given by $(n>\nu)$,

$$\omega_e{}^2 = (n-\nu)^2\ \Omega^2 \approx \kappa_e{}^2 + 1/\tau_e{}^2 \tag{8}$$

and the growth rate is

$$1/T = (\mu\tau_e)\ \frac{\omega_e\tau_e}{2}\ \Omega\Delta\ . \tag{9}$$

<u>Application to the Main Ring</u>

$N = 6.5 \times 10^{12}$

$R = 10^5$ cm

$a = 0.1$ cm

$\gamma = 50$

$\nu = 19.25$

$\Omega = 3 \times 10^5\ 5^{-1}$

$\alpha = 1/300$.

We take also

$$\tau_e \sim 10^{-9}\ \mathrm{s} \qquad \text{and} \qquad \tau_i \sim 2 \times 10^{-5}\ \mathrm{s}.$$

The electron and ion frequencies are

$$\kappa_e^2 = 5.2 \times 10^{17} \ s^{-2}$$

$$\kappa_i^2 = 1.4 \times 10^{14} \ s^{-2} \quad \text{(Hydrogen)}.$$

The ν-shift in the case of 100% neutralization is, from (6),

$$\Delta = 5.5 \times 10^{-3} .$$

We derive the frequency of the "electron resonance" from (8)

$$\omega_e/2\pi \sim 200 \text{ MHz} \tag{10}$$

which corresponds to $n \sim 4100$.

We have the growth rate from (9)

$$1/T = 10^3 \ (\mu\tau_e)$$

which corresponds to a growth time of ~40 msec if $\mu\tau_e = 2.5\%$, a number which is not at all unreasonable.

The high frequency (10) explains why no collective motion was observed and why the feedback system was uneffective.

It remains to explain why (a) the instability occurs at 50 GeV, (b) the instability is radial and not vertical, and (c) there is a threshold current. A glance at the above equations shows that the instability so far described by our theoretical model is weakly energy dependent(*). Nevertheless, it is not

(*)Observe that $a^2 \sim 1/\gamma$ in Eq. (6) for Δ. This also gives, at most, a $\gamma^{\frac{1}{2}}$ dependence for the growth rate (9); certainly not enough to explain the strong energy dependence in the main ring, (see Fig. 2).

difficult (see Eq. (7), for instance) to link our model to the resistive wall theory. Thus we know that a frequency spread makes the beam stable above some intensity value. Likely, at the energy of 50 GeV and maximum intensity, there is no longer enough frequency spread to make the beam stable on the radial plane. Then, beam loss occurs until a new intensity value is reached such that the stabilizing mechanism (Laudau damping) has effect again.

Final Observation

The instability recently discovered in the main ring, we believe, has no effect on the performance of the main ring. It is sufficient to eliminate the high-pressure bumps, or install clearing field electrodes and the beam will be stable again. The experiment so far conducted has only an "euristic" interest.

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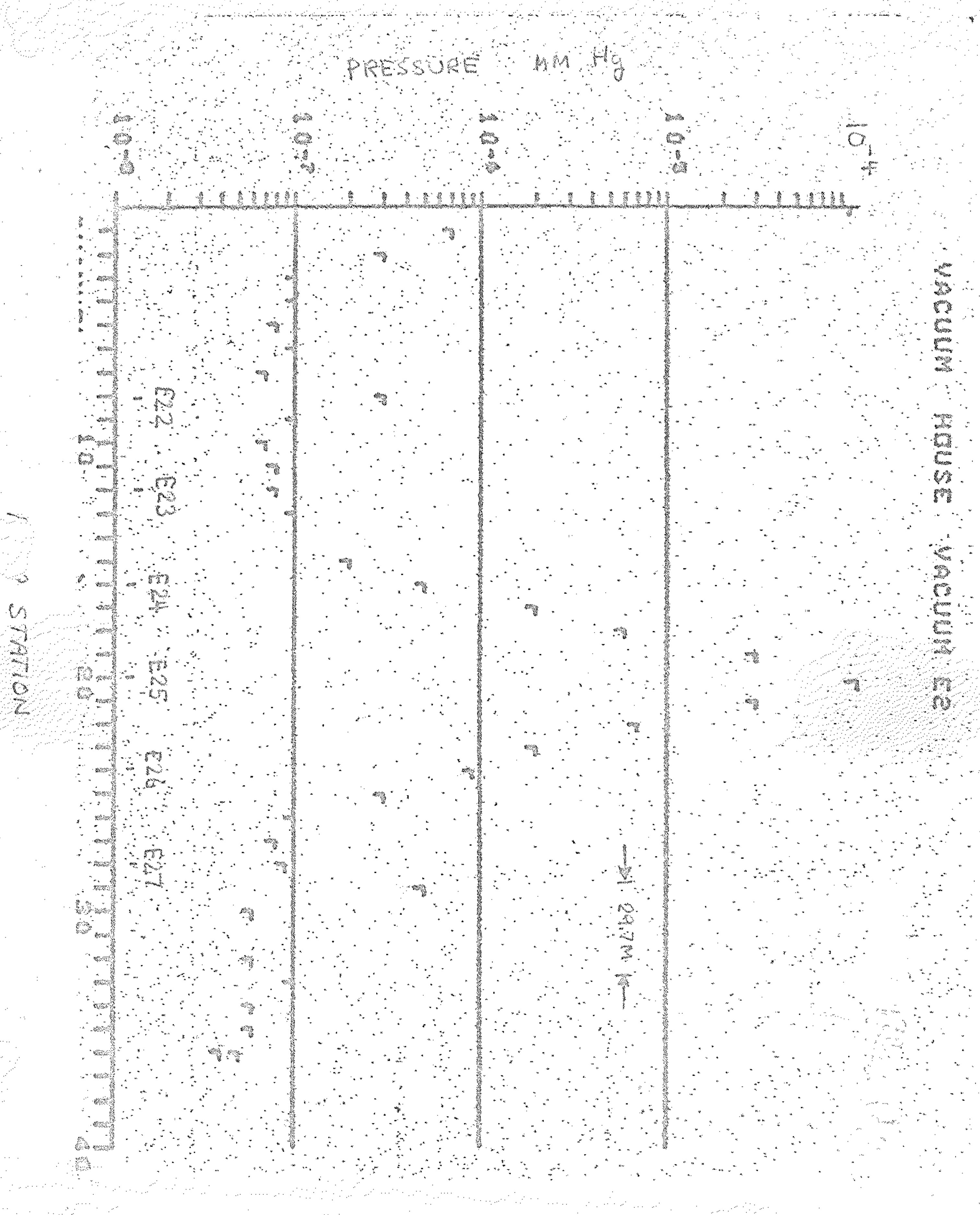
PRESSURE MM Hg
VACUUM HOUSE VACUUM E2
STATION
E22
E23
E24
E25
E26
E27
227M

Figure 2